The Particulate Separation Team

FY01 TECHNICAL PROGRESS REPORT

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DESCRIPTION: The research activities in this team are to stimulate, evaluate, and develop efficient, reliable and affordable high temperature and high pressure environmental control technologies to be integrated with the clean and efficient coal-based power plants of the 21st Century. Major R&D facilities include a hot gas stream clean-up test facility (HGSCTF), a particle deposition control facility (PDC), and a particle characterization laboratory (PCL). R&D programs consist primarily of two parts: (1) support domestic industries' R&D activities, including project collaboration with Southern Company Services' (SCS) particle filtration demonstrations at the Power Systems Demonstration Facility (PSDF) in Wilsonville, AL and (2) pursue in-house R&D activities.

RESEARCH OBJECTIVES:

During this fiscal year, the research objectives defined above are listed in the following table.

	Support Domestic Industries' R&D	**Pursue In-House R&D**
For Reduced Cost	♦ High surface area filter element – complete OPM Blasch's advanced cross-flow filter test ♦ Increased cyclic endurance life CRADA	♦ High surface area filter element - evaluate DOE/NETL patented concentric annular rigid (CAR) filter configuration

	Support Domestic Industries' R&D	Pursue In-House R&D
For Improved Reliability	♦ Advanced filter material & fabrication techniques - ASMT Fe_2O_3 and other metal oxide CRADA ♦ Filter safeguard devices - test SRI, Siemens-Westinghouse filter safeguard devices	♦ Mathematical modeling - filter safeguard devices ♦ Computer-controlled smart filter system ♦ In-situ non-destructive & non-contact (NC/NDE) filter evaluation

LONG TERM GOALS / RELATIONSHIP TO NETL'S PRODUCT LINE:

Under the V21 Transition Plan in NETL's Vision 21 Program Plan, hot particulate removal is identified as one of the 8 activities in the existing Pressurized Fluidized Combustion (PFBC) Program to be rolled into the Vision 21 Program. Hot particulate filter reliability and adaptation to other markets is also identified as one of the 5 activities among the exiting PFBC Program to be continued separately. Under "Status of Enabling and Supporting Technologies," reducing the cost of filter systems was called out as a Vision 21 need. This progress report presents our efforts to support and develop an efficient, reliable, and affordable hot gas particulate filter system for the PFBC Program and its future integration with the Clean Energy Plants for the 21st Century Program.

SUMMARY ACCOMPLISHMENTS:

We established a results-oriented R&D collaboration with SCS particle filtration demonstration at PSDF. SCS recommended a list of R&D projects that would be best performed in a laboratory facility to support field demonstrations. The following table highlights FY01 accomplishments.

	Support Domestic Industries' R&D	Pursue In-House R&D
For Reduced Cost	♦ Increased cyclic endurance life – completed NETL-Technetics joint final CRADA report, recommended SCS field trial at PSDF	♦ High surface area filter element - DOE/NETL patented (CAR) filter element under testing

	Support Domestic Industries' R&D	Pursue In-House R&D
For Improved Reliability	♦ Filter safeguard devices – completed lab evaluation of ♦ SRI - full-flow mechanical safeguard device ♦ Siemens-Westinghouse barrier filter type safeguard device	♦ Scientific particle and filter cake database - expanded with PSDF char ♦ Mathematical modeling – completed performance model for filter safeguard devices ♦ Computer-supervised smart filter system – established NETL Barrier Filtration Model and completed installation of real-time particle monitoring systems ♦ QC NC/NDE of filters - contracted to University of Alabama at Birmingham, AL

Background:
DOE's approach for developing the technology needed for ultra-clean, 21st century energy plants is called Vision 21. The goal of Vision 21 is to effectively remove, at competitive costs, environmental concerns associated with the use of fossil fuels for producing electricity, transportation fuels, and high-value chemicals. The program builds off of a suite of advanced technologies growing out of ongoing research and development (R&D) sponsored by DOE. As a vital part of the R&D program, efficient, reliable, and affordable particle filtration systems are essential for gasification-based plants using coal or solid fuel feedstocks. NETL has been investigating methods to characterize the operation of a rigid barrier filter system under high temperature and pressure applications. A mathematical model complete with filtration, regeneration, and particle re-deposition is presented here to describe the dynamics of a rigid barrier filter system. This model can also be used to construct a computer-supervised smart filter system to warrant its system reliability. The required real-time monitoring devices are currently under laboratory investigation.

General description of a rigid barrier filter system

For high temperature and pressure particle filtration, most rigid filters investigated have the geometry of a candle. To withstand the high operating temperature and corrosive environment, candles are usually made of monolithic silicon carbide, composite oxide fibers, iron-aluminide, or other alloy sintered and felted metals. Figure 1 illustrates a typical high temperature and pressure rigid barrier filter system.

As shown in Figure 1, the tube sheet physically separates the dirty and clean gas sides. The incoming dirty gas passes through the candle filters, which functionally separate the entrained particles, build up the filter cake, and let clean gas pass through. This particle filtration process goes on until such time that a limiting pressure drop is reached to initiate the filter regeneration. At the filter regeneration, a high-pressure back-pulse is introduced to dislodge the filter cake to recover the filter system pressure drop. Due to the short duration of the high-pressure back-pulse, of the order of a fraction of second, the dislodged filter cake, if not settled out at the end of regeneration, will be returned or re-deposited to the filter surface during following filtration cycle. Particle re-deposition of various degrees has indeed been observed for all rigid barrier filter systems. This unavoidable particle re-deposition, however, introduces an additional filter system pressure drop, known as the residual pressure drop, at the completion of filter regeneration. The entire filter system pressure drop, or the tube sheet pressure drop, under steady state operation thus can be described to consist of three components: the conditioned filter element pressure drop, the residual pressure drop, and the filter cake pressure drop. A mathematical model complete with these three pressure drop components is presented below to describe the dynamic nature of a rigid barrier filter system, including a tool to quantify the residual pressure drop.

Residual pressure drop formation

Nomenclature:

ΔP_f	Filter system pressure drop or tube sheet pressure drop
$\Delta P_{v\,f}$	Virgin filter pressure drop
ΔP_r	Residual pressure drop
ΔP_c	Fresh filter cake pressure drop
u_f	Face velocity
k_f	Virgin filter resistivity, defined as $k_f = \Delta P_{v\,f} / u_f$
K_2	Filter cake specific resistance coefficient
C	Particle concentration, weight/unit volume
t	Time
T	Filtration period, duration of filtration before filter regeneration
γ	Fraction of dislodged filter cake re-deposited following filter regeneration
σ_f	Filter cake areal density, defined as $\sigma_f = C\, u_f\, t$
σ_r	Residual cake areal density, defined as $\sigma_r = \gamma\, \sigma_f$

Filter Regeneration at a Predetermined Time Interval

The overall filter system pressure drop, or the tube sheet pressure drop, is the sum of pressure drops of the virgin filter, the residual filter cake due to particle re-deposition, and the fresh filter cake. That is

$$\Delta P_f = \Delta P_{vf} + \Delta P_r + \Delta P_c$$

Initially, a virgin filter offers no resistance, $\Delta P_r = 0$.

At face velocity of u_{f1}, particle concentration C_1, and filtration duration of t_1, the overall filter system pressure drop is

$$\Delta P_{f1} = k_f\, u_{f\,1} + K_{21}\, \sigma_f\, u_{f\,1} \qquad \textbf{(1)}$$

K_{21} indicates possible variations in particle size distributions.

At the end of the filtration period t_1, filter regeneration begins. Unlike fabric filters, barrier filter regeneration is assumed to have all the resident filter cake removed from its filter surface, re-entrained in the process flow stream, and then have a fraction, γ_1, re-deposited back onto the filter surface at the resumption of filtration. The 1- γ_1 fraction is removed from the process stream and settles out in the ash hopper. The re-deposited γ_1 fraction forms the residual filter cake representing the residual filter pressure drop.

Assuming this residual filter cake has the same specific resistance coefficient as the fresh filter cake, its pressure drop would then be

$$\Delta P_{r1} = \gamma_1 (K_{21}\ \sigma_{f\,1})\ u_{f\,2} = K_{21}\ (\gamma_1\ \sigma_{f\,1})\ u_{f\,2} = K_{21}\ \sigma_{r1}\ u_{f\,2}$$

This completes the first filtration and regeneration cycle.

Following the same reasoning, at face velocity u_{f2}, particle concentration C_2, and filtration period t_2, the total filter system pressure drop at the second filtration cycle is

$$\begin{aligned}\Delta p_{f\,2} &= k_f\ u_{f\,2} + K_{21}\ \sigma_{r\,1}\ u_{f\,2} + K_{22}\ \sigma_{f\,2}\ u_{f\,2} \\ &= k_f\ u_{f\,2} + K_{21}\ (\gamma_1\ \sigma_{f1})\ u_{f\,2} + K_{22}\ \sigma_{f\,2}\ u_{f\,2}\end{aligned} \quad \textbf{(2)}$$

At the end of filtration period t_2, the total filter cake is now

$$\sigma_{r1} + \sigma_{f\,2} = \gamma_1\ \sigma_{f\,1} + C_2\ u_{f\,2}\ t_2$$

Filter regeneration at a re-deposition fraction of γ_2 would produce a residual areal density of

$$\sigma_{r\,2} = \gamma_2\ (\sigma_{r\,1} + \sigma_{f\,2}) = \gamma_2\ \gamma_1\ (\sigma_{f\,1}) + \gamma_2\ (\sigma_{f\,2})$$

Similarly, following the same approach in deriving Equation (2), it can be seen that at face velocity $u_{f\,3}$, particle concentration C_3, and filtration period t_3, the total filter system pressure drop at the third filtration cycle is

$$\begin{aligned}\Delta p_{f\,3} &= k_f\ u_{f\,3} + K_{22}\ \sigma_{r2}\ u_{f\,3} + K_{23}\ \sigma_{f\,3}\ u_{f\,3} \\ &= k_f\ u_{f\,3} + K_{22}\ [\gamma_2\ \gamma_1\ (\sigma_{f\,1}) + \gamma_2\ (\sigma_{f\,2})]\ u_{f\,3} + K_{23}\ \sigma_{f\,3}\ u_{f\,3}\end{aligned} \quad \textbf{(3)}$$

It is now apparent that at the nth filtration cycle at face velocity $u_{f\,n}$, particle concentration C_n, and filtration period t_n, the total filter system pressure drop at steady state is

$$\begin{aligned}\Delta p_{f\,n} &= k_f\ u_{f\,n} + K_{2\,(n-1)}\ \sigma_{r\,(n-1)}\ u_{f\,n} + K_{2\,n}\ \sigma_{f\,n}\ u_{f\,n} \\ &= k_f\ u_{f\,n} + K_{2\,(n-1)}\ [\gamma_{n-1}\ \gamma_{n-2} \cdots \gamma_1\ (\sigma_{f\,1}) + \gamma_{n-2}\ \gamma_{n-3} \cdots \gamma_1\ (\sigma_{f\,2}) + \cdots \\ &\qquad + \gamma_{n-1}\ (\sigma_{f\,(n-1)})]\ u_{f\,n} + K_{2\,n}\ \sigma_{f\,n}\ u_{f\,n}\end{aligned} \quad \textbf{(4)}$$

Generalization

For constant particle concentration C, constant specific resistance coefficient K_2, constant face velocity u_f, predetermined filtration period T, and constant re-deposition rate γ, Equation (4) reduces to

$$\begin{aligned} \Delta p_{f\,n} &= k_f\ u_f\ + K_2\ \sigma_{r\,(n-1)}\ u_f\ + K_2\ \sigma_f\ u_f \\ &= k_f\ u_f\ + K_2\ (\gamma^{n-1} + \gamma^{n-2} + \cdots + \gamma^2 + \gamma)\ \sigma_f\ u_f\ + K_2\ \sigma_f\ u_f \end{aligned} \quad \textbf{(5)}$$

For $\gamma < 1$, the geometric series in the parenthesis converges when the filter system reaches its steady state. Equation (5) reduces to

$$\begin{aligned} \Delta p_{f\,n} &= k_f\ u_f\ + K_2\ [\gamma/(1-\gamma)]\ \sigma_f\ u_f\ + K_2\ \sigma_f\ u_f \\ &= k_f\ u_f\ + K_2\ [\gamma/(1-\gamma)]\ C(u_f)^2\ T + K_2\ C(u_f)^2\ T \end{aligned} \quad \textbf{(6)}$$

From the observed filter system pressure drop versus time characteristics, the maxim tube sheet pressure drop at T according to Equation (6) is

$$\Delta P_{f\,n\,(max)} = k_f\ u_f\ + K_2\ [\gamma/(1-\gamma)]\ C(u_f)^2\ T + K_2\ C(u_f)^2\ T \quad \textbf{(7)}$$

After filter regeneration, the minimum tube sheet pressure drop according to Equation (6) is

$$\Delta P_{f\,n\,(min)} = k_f\ u_f\ + K_2\ [\gamma/(1-\gamma)]\ C(u_f)^2\ T \quad \textbf{(8)}$$

Taking the difference of Equations (7) and (8),

$$\Delta P_{f\,n\,(max)} - \Delta P_{f\,n\,(min)} = K_2\ C(u_f)^2\ T \quad \textbf{(9)}$$

Also, from Equation (8), we have

$$\gamma/(1-\gamma) = (\Delta P_{f\,n\,(min)} - \Delta P_{vf})\ /\ [\ K_2\ C(u_f)^2\ T\ ] \quad \textbf{(10)}$$

Solving Equations (9) and (10), the re-deposition fraction γ reduces to experimentally observable quantities. The re-deposition fraction γ is

$$\gamma = (\Delta P_{f\,n\,(min)} - \Delta P_{vf})\ /\ (\Delta P_{f\,n\,(max)} - \Delta P_{vf}) \quad \textbf{(11)}$$

For varying particle concentration C, varying specific resistance coefficient K_2, varying face velocity u_f, and varying filtration period T, the re-deposition fraction γ is best followed by a real time data acquisition system.

In fact, rigid barrier filters are not absolute filters. New filters, after an initial use, quickly reach a conditioned steady-state which has a different but higher pressure-drop characteristic than in its virgin state, due primarily to fine particles which become trapped within the filter element.

Therefore, ΔP_{vf} in Equation (11) needs be substituted with the conditioned steady-state pressure drop.

DISCUSSION

Following Equations (1) to (4), a program can be written to track down the dynamic nature of a rigid barrier filter system operation. Figure 2 illustrates typical filter system pressure drop versus time characteristics separating PFBC particles under varying face velocities. This figure also shows different degrees of re-deposition at various face velocities. A change of particle characteristics will significantly change the filter system operating characteristics. To assure a reliable filter system operation for protection of a downstream gas turbine, continuous real time particle monitoring of particle concentration and particle size distribution at the filter system inlet and outlet are essential. The inlet particle concentration provides information to extract the numerical filter cake specific resistance coefficient from the slope of the filter pressure drop characteristics. The inlet particle size distribution provides additional information on the filter cake related to the increasing slope of the filter pressure drop characteristics, ineffective filter regeneration, and the undesirable degree of particle re-deposition. The outlet particle concentration and size distribution provide information to meet the environmental regulations and the gas turbine protection requirements. Currently, as shown in Figure 3, a light scattering particle-monitoring device is setup in the High-Temperature Gas-Stream Cleanup Test Facility for evaluation. Successful completion of this evaluation would lead to an ultimate computer-supervised smart filter system to assure reliability. It is anticipated that a smart filter system will also provide operating information updates, malfunctioning alarms, and self-activated measures such as adjusting the cleaning frequency, intensity, and back-pulse duration.

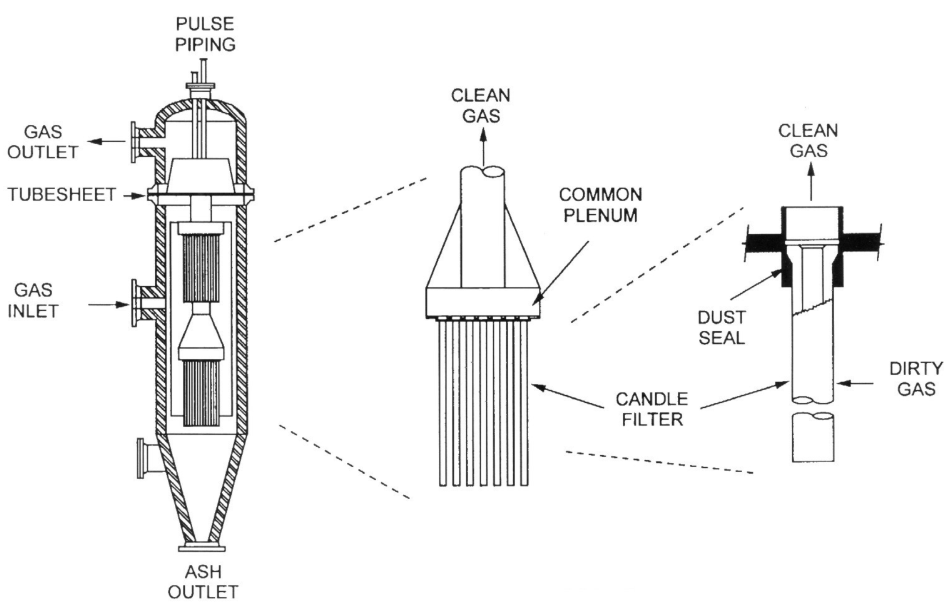

Figure 1. Typical rigid barrier high-temperature filter system for

high-pressure applications

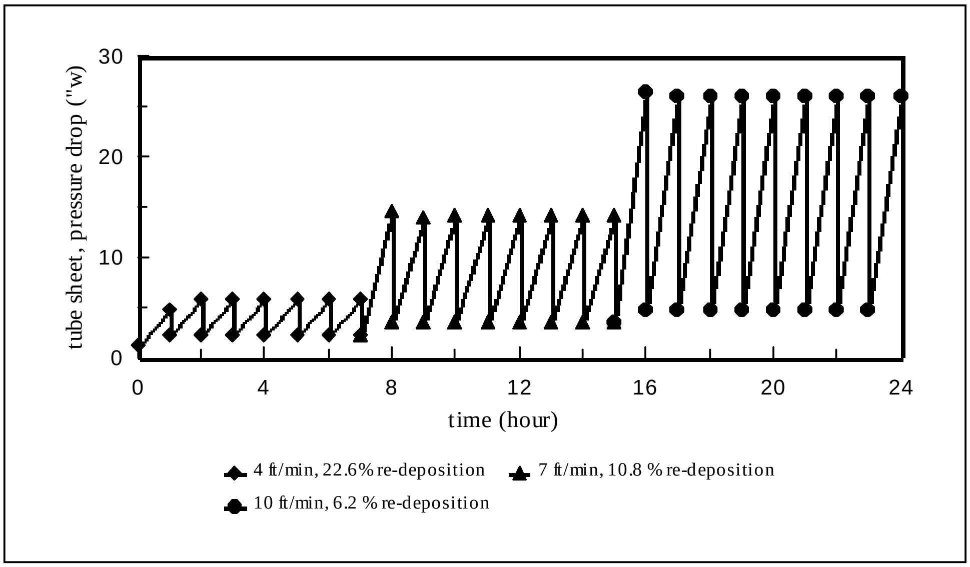

Figure 2. Typical rigid barrier filter system pressure-drop characteristics:
Feltmetal candle filter, 1.5mlong x 60mm o.d.
PFBC Tidd-Brilliant Demonstration Plant flyash.
1500 F., 150 psig, 3000 ppmw particle loading.
Tube sheet pressure drop <2.5 psi (69”-w).
Optimized regeneration: dislodged cake size = filter cake thickness.

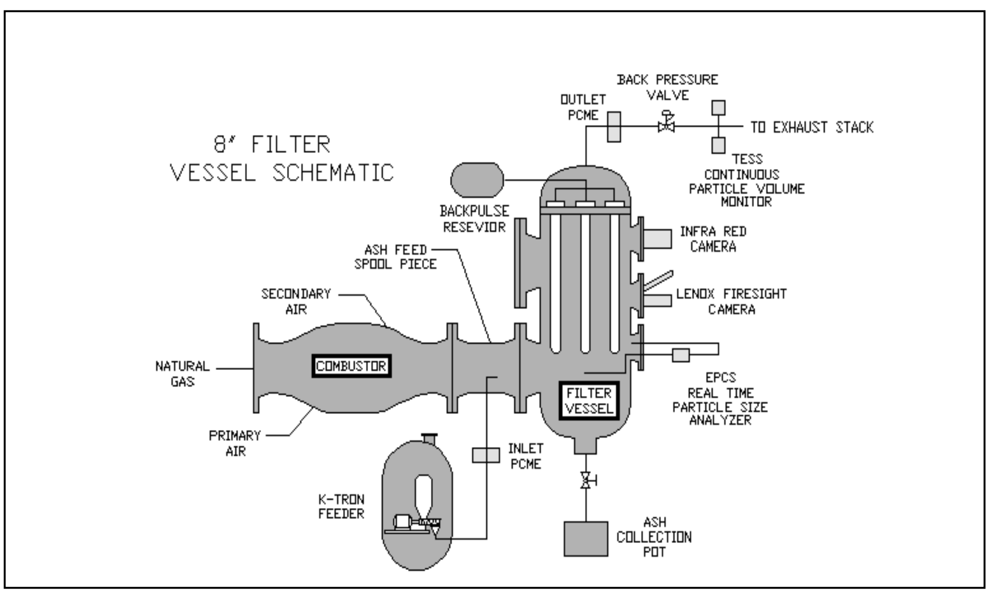

Figure 3. Real-time particle monitoring instrumentation for a computer-

supervised smart filter system

The Combustion Technologies Product Team sponsors this team's research activities. The entire team made technical contributions. For additional information about the HGSCTF facility, contact E. Saab; PDC, NC/NDE, and particle monitoring, contact P. Yue; PCL, contact S. Beer; in-house filtration model and other CRADAs, Dave Wildman. The NETL Engineering Applications and Operations Division provided the facility and engineering design of all the projects and performed the operation and testing. NETL site support contractor Parsons Infrastructure & Technology provided the facility construction, component fabrication, data acquisition, and instrumentation supports.